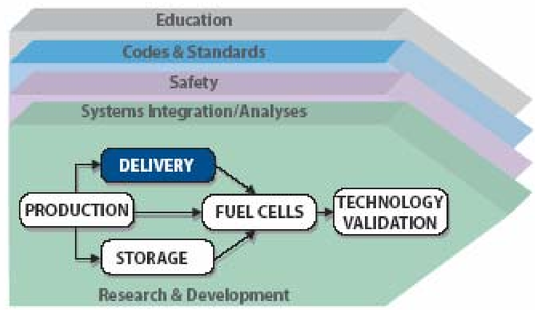
3.2 Hydrogen Delivery

Hydrogen must be transported from the point of production to the point of use. It also must be compressed, stored and dispensed at refueling stations or stationary power facilities. Due to its relatively low volumetric energy density, transportation, storage and final delivery to the point of use can be one of the significant cost and energy inefficiencies associated with using hydrogen as an energy carrier.



3.2.1 Technical Goal and Objectives

Goal

Develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.

Objectives

- By 2006, define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the transition and long-term use of hydrogen for transportation and stationary power.
- By 2010, reduce the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users to <$0.90/gge of hydrogen.[1]
- By 2010, reduce the cost of compression, storage and dispensing at refueling stations and stationary power facilities to <$0.80/gge of hydrogen (independent of transport).[1]
- By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen in total.[1]

3.2.2 Technical Approach

The Hydrogen Delivery Program element is focused on meeting the hydrogen delivery objectives outlined in Section 3.2.1 by conducting R&D through industry, national laboratory and university projects. Projects will address the barriers outlined in Section 3.2.4.2, and progress toward meeting the objectives will be measured against the technical targets outlined in Section 3.2.4.1. Delivery efforts will be coordinated with any related activities in the DOE Office of Fossil Energy and the Department of Transportation.

Infrastructure Options

The hydrogen production strategy greatly affects the cost and method of delivery. If the hydrogen is produced centrally, the longer transport distances can increase delivery costs. It can be produced semi-centrally (within 50-100 miles of the point of use) to reduce this transport distance. Distributed production at the point of use eliminates the transportation costs but results in higher production costs because the economy of larger scale production is lost. In all cases, the delivery costs associated with compression, storage and dispensing at the refueling station or stationary power site are significant and need to be minimized.

There are three primary options for hydrogen delivery. One option is that it can be delivered as a gas in pipelines or high-pressure tube trailers. This is illustrated in Figure 3.2.1. This option offers the possibility of transporting a mixture of hydrogen and natural gas in the existing natural gas pipeline infrastructure followed by separation and purification of the hydrogen. Hydrogen can also be liquefied and delivered in cryogenic tank trucks. This is illustrated in Figure 3.2.2. Gaseous and liquid delivery are used today but there is only a very limited hydrogen pipeline infrastructure for gaseous service.

Figure 3.2.1. Gaseous Hydrogen Delivery Pathway

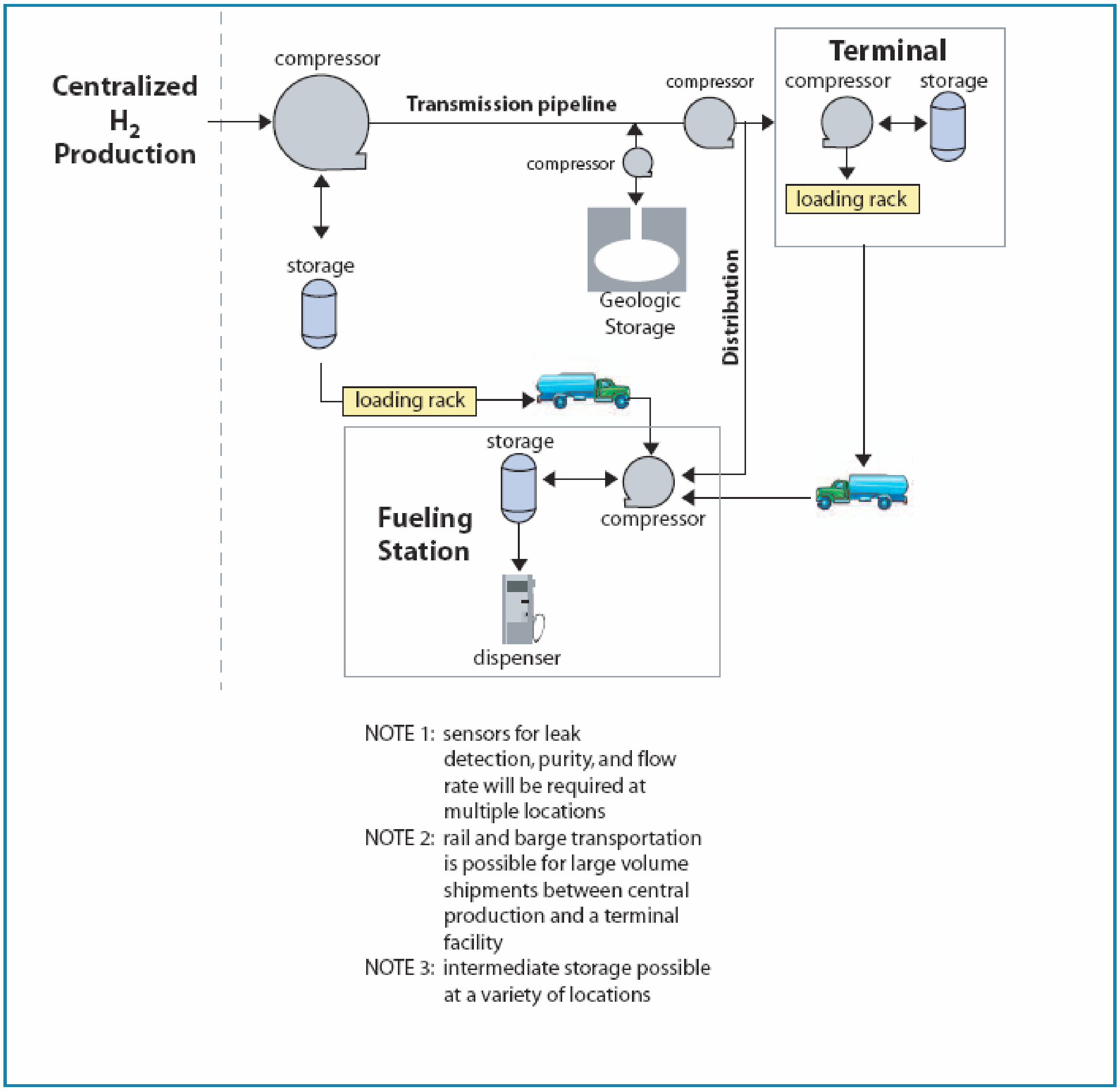
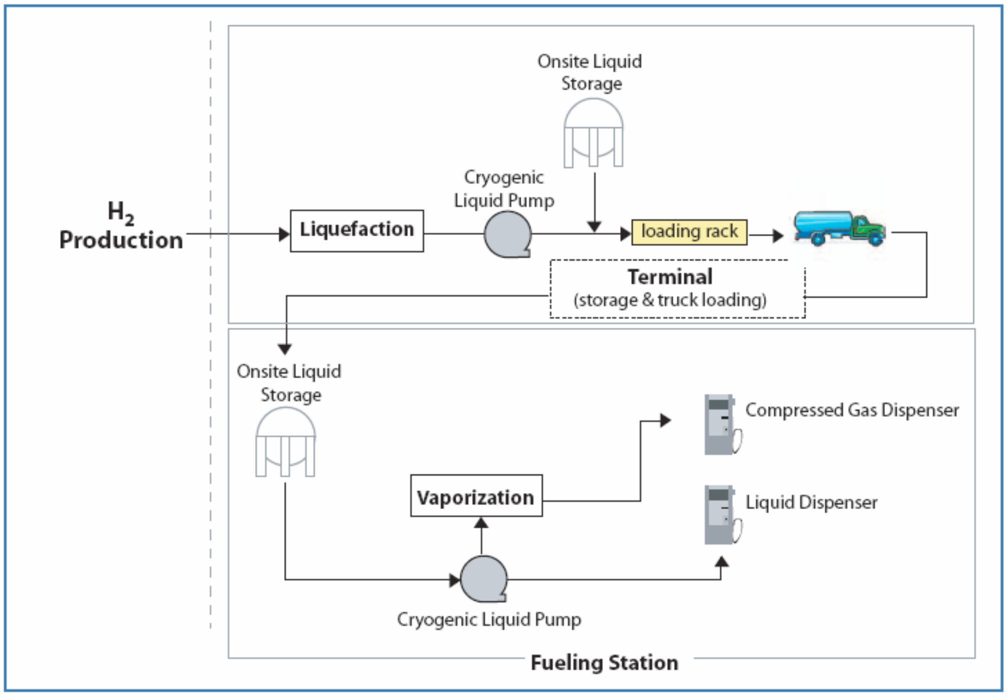
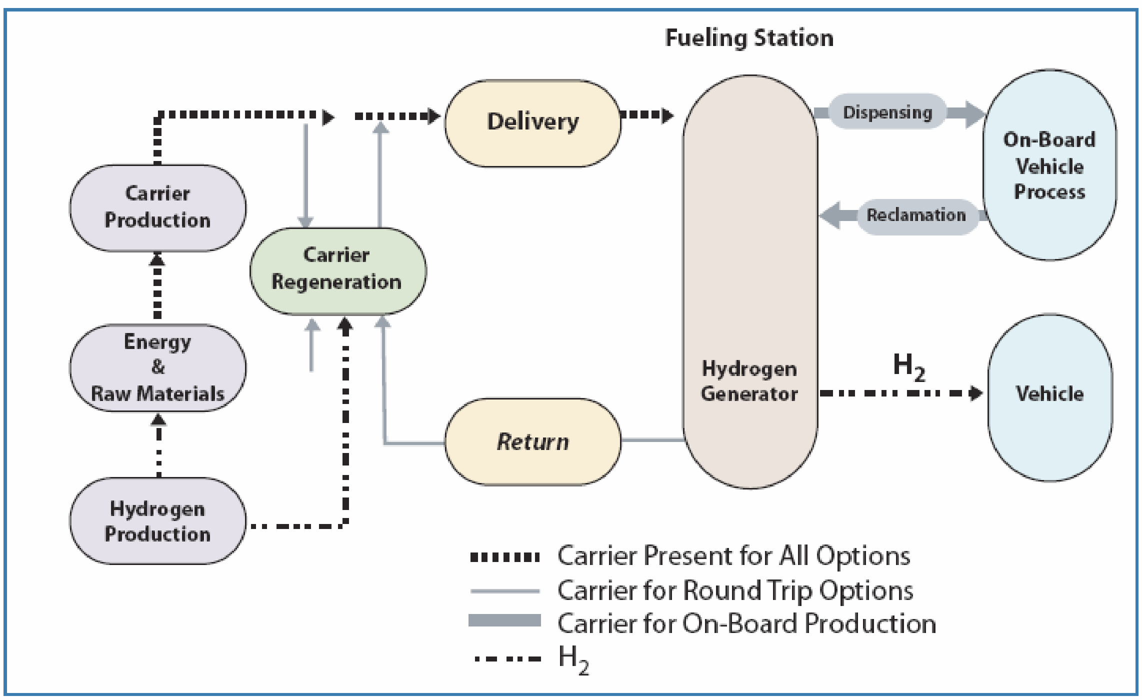


Figure 3.2.2. Cryogenic Liquid Hydrogen Delivery



A third option is higher volumetric energy density carriers such as natural gas, methanol, ethanol or other liquids derived from renewable biomass that can be produced, transported to the point of use, and reformed to hydrogen. Novel carriers such as metal hydrides or other hydrogen containing solids or liquids that can be treated to release hydrogen at a refueling station or stationary power location or possibly even directly on-board a vehicle are other promising alternatives. This carrier approach is illustrated in Figure 3.2.3.

Figure 3.2.3. Novel Carrier Pathway



These primary delivery pathways can also be used in combination. For example, gaseous hydrogen could be delivered by pipeline to a terminal where it could be liquefied and then delivered by cryogenic tank truck or transformed to a novel carrier system for delivery. There are many potential components to a complete hydrogen delivery infrastructure:

- Pipelines
- Compression
- Liquefaction
- Tube Trailers, Cryogenic Liquid Trucks, Rail, Barges, Ships (liquid and gaseous H2)
- Liquid and Gaseous Tanks
- Geologic Storage
- Terminals
- Separation/Purification
- Dispensers
- Carriers

One advantage of hydrogen is that it can be produced from a variety of feedstocks in a variety of ways. It will be produced from a spectrum of feedstocks and production technologies over the course of its introduction and long-term use as a primary energy carrier. Similarly, the delivery technology may well encompass several options over the short and long terms. The transportation methods used at the early stages, when hydrogen volumes are relatively low, may be different than those used when hydrogen is used in large quantities as a primary energy carrier. At very large volumes, an extensive pipeline infrastructure is currently the most cost-effective and energy efficient manner to transport hydrogen to much of the market as is done with natural gas today. However, other methods, such as, cryogenic liquid truck delivery or distributed natural gas or liquid reforming, will be needed for the transition period. In any event, lower cost and more energy-efficient technologies are needed for hydrogen transportation and handling for hydrogen to become a major energy carrier.

Terminals, Trucks, Rail Barges, and Ships

The current petroleum delivery infrastructure includes terminals, trucks, rail, barges and ships for delivery. Other than truck delivery, none of these delivery infrastructure modes are used today for hydrogen delivery. For the delivery infrastructure for hydrogen as a major energy carrier, some of these other delivery infrastructure elements may be needed.

Bulk Storage

Storage within the hydrogen delivery infrastructure will be important to provide surge capacity for daily and seasonal demand variations. The most common pressure vessels for gaseous hydrogen are steel tubes. They can be used to store hydrogen at 6,000 psi or higher. They are often manifolded together allowing for larger storage capacity. Hydrogen is also stored as a cryogenic liquid due to its higher volumetric energy density and thus smaller footprint. This approach is not a low cost option due to the high cost of hydrogen liquefaction.

Geologic storage is routinely used to provide seasonal surge capacity in the natural gas delivery infrastructure. Very large volumes of natural gas are stored in natural geologic formations such as salt caverns under modest pressure (typically about 2000 psi or less). The hydrogen infrastructure will likely require similar bulk storage capability. Besides naturally-occurring geologic formations, storing hydrogen in specially engineered rock caverns, referred to as lined rock caverns (LRC), offers another possibility. Research into the suitability of geologic storage is needed. Hydrogen is a much smaller molecule than natural gas and has a much higher diffusivity. Containment within geologic storage may be more challenging and potential environmental impacts need to be investigated.

Novel hydrogen carriers could be very useful for off-board hydrogen storage. For example, a solid that could reversibly adsorb and desorb significant amounts of hydrogen and store it at low pressures could significantly reduce the compression costs associated with gaseous storage and might prove to have lower capital cost requirements as well.

Interface with On Board Vehicular Storage of Hydrogen

The technology selected for storing hydrogen on board vehicles may affect the hydrogen delivery system and infrastructure. Delivery and on-board storage need to be integrated at some junction in the system. For example, the on-board storage system could be a solid carrier that receives hydrogen gas directly from a dispenser at a refueling station. On the other hand, if an on-board carrier system requiring off-board regeneration is selected, the hydrogen delivery system will need to cost-effectively accommodate this approach. In addition, vehicle interface technologies will need to be jointly addressed by both the Delivery and Storage Program elements, as promising options are selected. The Hydrogen Delivery milestone chart in Section 3.2.6 and the Hydrogen Storage milestone chart in Section 3.3.6 show inputs and outputs between the Delivery and the Storage Program elements that address these interactions.

Research Strategy

To enable the introduction of hydrogen as an energy carrier, a key initial focus of the Hydrogen Delivery Program element will be on hydrogen delivery research challenges at refueling stations and stationary power sites with respect to compression and storage technology. The improved technologies necessary for transport of hydrogen from more central production facilities will be researched in a parallel effort but with greater emphasis later in the program. After 2015, the remaining federal effort will likely be selective and only fund new concepts that could make further significant impacts on delivery costs or energy efficiencies.

3.2.3 Programmatic Status

Specific focus on hydrogen transportation and delivery in the Program is now underway. The importance of this part of the value chain was highlighted in the National Hydrogen Energy Roadmap published in the fall of 2002 and more recently by the National Academies[2]. The Hydrogen Delivery Program element is now being initiated. The current projects that pertain to this Program element are shown in Table 3.2.1.

Table 3.2.1. Current Hydrogen Delivery Projects

Challenge	Approach	Activities
Pipelines: Reduce the capital costs and ensure safety and reliability	• Develop new and improved materials for pipeline delivery of hydrogen	• Oak Ridge National Laboratory (ORNL): Improved steel materials and welds. • ORNL: Low-cost fiber reinforced polymer (FRP) composite pipelines. • Savannah River National Laboratory (SRNL): Natural Gas pipelines for hydrogen use. • Secat, Inc. ORNL, ASME, U. of Illinois, Applied Thin Films, Columbia Gas, CCC Coatings, ATC, and Oregon Steel Mills: Pipeline and weld materials, and coatings testing and modeling. • U. of Illinois: Lifetime prediction model for pipeline steels in hydrogen service.
Carriers: Develop carriers that can enable low cost hydrogen delivery	• Explore novel liquid and solid carrier technology for use in hydrogen delivery.	• Air Products & Chemicals, Inc., UTRC, and Pennsylvania State University: Reversible liquid carrier for integrated hydrogen, storage, and delivery.
Compression: Increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compression	• Develop improved compression technologies for hydrogen	• Argonne National Laboratory (ANL): Novel screw compression technology for hydrogen service. • HERA: Novel hydride compression and purification
Analysis: Identify the better options for cost-effective and energy-efficient hydrogen delivery infrastructure for the introduction and long-term use of hydrogen	• Analyze systems and infrastructures for delivery of gaseous and liquid hydrogen and novel solid/liquid hydrogen carriers	• National Renewable Energy Laboratory (NREL), ANL and Pacific Northwest National Laboratory (PNNL): Components modeling; compression technology and issues; ethanol delivery infrastructure characterization; and hydrogen delivery scenario modeling. • Nexant, Inc., Air Liquide, ChevronTexaco, NREL, Gas Technologies Institute, Pinnacle West, and TIAX: Cost/environmental analyses for delivery scenarios as a function of time and demand.
Off-Board Storage: Reduce the cost and footprint of hydrogen storage at refueling stations.	• Analyze available technology options for bulk storage of hydrogen at a refueling station. Address capital cost, operating costs, footprint, fuel capacity and safety.	• Gas Technology Institute: Options for off-board storage at refueling stations with emphasis on the suitability of underground liquid hydrogen storage. • Lawrence Livermore National Laboratory: Composite materials and structures for high-pressure off-board storage and tube trailers.

Liquefaction: Reduce the cost and improve the energy efficiency of hydrogen liquefaction.	• Explore new approaches to hydrogen liquefaction.	• NCRC Corporation, Promethius Energy Inc., and H2 Storage Solutions: Efficient and inexpensive magnetic liquefaction technology. • Gas Equipment Engineering Corporation and R&D Dynamics: Turbocompressor/expander technology for liquefaction.

Research and development of metal hydrides and other novel solid or liquid carriers of hydrogen useful for storage (see section 3.3) may also find use for hydrogen delivery.

3.2.4 Technical Challenges

Cost and Energy Efficiency

The overarching technical challenge for hydrogen delivery is reducing the cost of the technology so that stakeholders can achieve a return on the investment required for this infrastructure. The energy efficiency of delivery also needs to be improved.

Current costs for the transport of hydrogen, with the exception of that transported through the very limited amount of hydrogen pipelines, is \$4-\$9/gge of hydrogen.[3] This is based on transport by gaseous tube trailers or cryogenic liquid trucks and is very dependent on amounts and distances. Pipeline transport costs are dependent on transport distance and the amount of hydrogen delivered. These transport costs do not include the delivery costs associated with compression, storage and dispensing at the point of use.

Hydrogen Quality Requirements

PEM fuel cells for automotive and other uses require very pure hydrogen (see Table 3.2.2). There also might be quality specifications for the final technology developed and adopted for on–board vehicle storage (see section 3.3). If the hydrogen is produced to these quality specifications, then the delivery infrastructure must ensure it does not contaminate the hydrogen. Alternatively, the hydrogen could be produced to somewhat lower quality levels and then be purified to specifications just prior to dispensing. The optimum purification strategy that will minimize overall costs will depend on the nature of the potential contamination issues and thus the technologies employed across production and delivery. The delivery research plan as depicted in Figure 3.2.5 has several inputs and outputs among Hydrogen Production, Delivery, Storage, Fuel Cells and Systems Analysis to help optimize this purification strategy.

Hydrogen Leakage

The hydrogen molecule is very small and diffuses more rapidly compared with other gases such as natural gas. This makes it more challenging to design equipment, materials, seals, valves and fittings to avoid hydrogen leakage. Currently hydrogen is used and handled in significant quantities in industrial settings in petroleum refining, ammonia production, and specialty chemicals production without significant leakage issues. Industrial hydrogen operations are monitored and maintained by skilled people. The delivery infrastructure for hydrogen use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering.

Infrastructure Trade-Offs

Options and trade-offs for hydrogen delivery from central, semi-central and distributed production to the point of use are not well understood. Analysis is needed to understand the advantages and disadvantages of the various energy sources and production and delivery technology options to guide research and investment efforts for the ultimate hydrogen infrastructure and for the most appropriate infrastructure to be used during the introduction of hydrogen as a primary energy carrier. Examples of some of these trade-offs include:

- Centrally producing a liquid fuel, such as ethanol from biomass, and then transporting this relatively high volumetric energy density fuel to a refueling station for reforming into hydrogen versus centrally producing hydrogen from biomass and then transporting the lower volumetric energy density hydrogen to the refueling station.
- Utilizing liquefaction and liquid truck delivery during the early transition period at low hydrogen demand rates versus installing some hydrogen delivery pipelines early. The former involves potentially less capital risk while the latter sets the stage for the longer term, lower cost delivery option when hydrogen is in high demand.
- Purifying hydrogen at the central production point to required final use specifications and designing the delivery infrastructure to avoid any contamination versus basic purification at the point of manufacture and final polishing purification just prior to the point of use.
- The cost of a novel solid or liquid hydrogen carrier delivery system without the need for compression versus the cost of gaseous delivery with compression.

3.2.4.1 Technical Targets

Table 3.2.2 lists the technical targets for the Hydrogen Delivery Program element.

The key to achieving the goal and objectives of the Hydrogen Delivery Program element is to bring down the costs, improve the energy efficiency and ensure reliable performance of the key delivery technologies; compression, liquefaction, pipelines and off-board bulk storage. The targets shown in Table 3.2.2 are based on an analysis of current technology and costs, estimates of what might be possible with technology advances, and the market-driven requirements for the total delivery system costs. Delivery system costs are a complex function of the technology, delivery distances, system architecture and hydrogen demand. The 2015 cost targets in the table are the estimated costs needed for these technologies to achieve the objective of the overall delivery system cost contribution to be < \$1.00/gge of hydrogen in 2015.

Initial targets are also given for hydrogen solid- or liquid-carrier technologies that could prove useful for hydrogen delivery. There are many possible options for use of hydrogen carriers within the delivery system.

An important emphasis of the Program is the transition period when hydrogen will start to become utilized in the transportation market. In the Production area, this results in an initial focus on distributed production at refueling stations. Delivery research will support this through an emphasis on the cost of compression and storage at refueling stations. This is also reflected in the targets.

All targets must be acheived simultaneously; however, status is not necessarily reported from a single system.

Table 3.2.2 Hydrogen Delivery Targets[a]				
Category	**2003 Status**	**2005**	**2010**	**2015**
Pipelines: Transmission				
Total Capital Cost ($M/mile) [b]	$1.20	$1.20	$1.00	$0.80
Pipelines: Distribution				
Total Capital Cost ($M/mile) [b]	$0.30	$0.30	$0.25	$0.20
Pipelines: Transmission and Distribution				
Reliability (relative to H2 embrittlement concerns and integrity) [c]	Undefined	Undefined	Understood	High (Metrics TBD)
H2 Leakage[d]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[e]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%) [f]	99%	99%	99%	99%
Capital Cost ($M/compressor)[g]	$18	$18	$15	$12
Compression: At Refueling Sites				
Reliability[e]	Unknown	Unknown	90%	99%
Hydrogen Energy Efficiency (%) [f]	94%	94%	95%	96%
Contamination [h]	Varies by Design	Varies by Design	Reduced	None
Cost Contribution ($/gge of H2) [i,j]	$0.60	$0.60	$0.40	$0.25
Liquefaction				
Small-Scale (30,000 kg H_2/day) Cost Contribution ($/gge of H_2) [k]	$1.80	$1.80	$1.60	$1.50
Large-Scale (300,000 kg H_2/day) Cost Contribution ($/gge of H_2) [k]	$0.75	$0.75	$0.65	$0.55
Small-Scale (30,000 kg H_2/day) Electrical Energy Efficiency (%) [k, l]	25%	25%	30%	35%
Large-Scale (300,000 kg H_2/day) Electrical Energy Efficiency (%) [k,l]	40%	40%	45%	50%
Carriers				
H2 Content (% by weight) [m]	3%	3%	6.6%	13.2%
H_2 Content (kg H_2/liter)	Undefined	Undefined	0.013	0.027
H2 Energy Efficiency (From the point of H2 production through	Undefined	Undefined	70%	85%

dispensing at the refueling site) [f]				
Total Cost Contribution (From the point of H2Production through dispensing at the reueling site) ($/gge of H2)	Undefined	Undefined	$1.70	$1.00
Storage				
Refueling Site Storage Cost Contribution ($/gge of H_2) [j, n]	$0.70	$0.70	$0.30	$0.20
Geologic Storage	Feasibility Unknown	Feasibility Unknown	Verify Feasibility for H2	Capital and operating cost <1.5X that for natural gas on a per kg basis
Hydrogen Quality [o]	**>98% (dry basis)**			

[a] All dollar values are in 2003 U.S. dollars

[b] The 2003 status is based on data from True, W.R.,"Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 16, 2002, pp 52-57. This article reports data on the cost of natural gas pipelines as a function of pipe diameter. It breaks the costs down by materials, labor, misc. and right of way. It is based on a U.S. average cost. A 15 inch pipe diameter was used for transmission and 2.5 inch for distribution. It was assumed that hydrogen pipelines will cost 30% more than natural gas pipelines based on advice from energy and industrial gas companies and organizations. The targeted cost reductions for 2010 and 2015 assume the right of way costs do not change.

[c] Pipeline reliability used here refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement or other issues causing cracks or failures. The 2015 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

[d] Hydrogen leakage based on the hydrogen that permeates or leaks from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2015 target is based on being equivalent to today's natural gas pipeline infrastructure based on the article: David A. Kirchgessner, et al, "Estimate of Methane Emissions from the U.S. Natural Gas Industry", Chemososphere, Vol.35, No 6, pp1365-1390, 1997.

[e] Compression reliability is defined as the percent of time that the compressor can be reliably counted on as being fully operational. The 2003 value for transmission compressors is based on information from energy companies that use these types and sizes of compressors on hydrogen in their own operations.

[f] Hydrogen energy efficiency is defined as the hydrogen energy (LHV) out divided by the sum of the hydrogen energy in (LHV) plus all other energy needed for the operation of the process.

[g] The 2003 value is based on data from "Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 4, 2000, p 78. The compressor capital cost data was plotted vs. the power required for the compressor using the natural gas transmission compressor data provided. The capital cost was increased by 30% as an assumption for higher costs for hydrogen compressors. The power required was calculated assuming 1,000,000 kg/day of hydrogen flow with an inlet pressure of 700 psi and an outlet pressure of 1,000 psi.

[h] Some gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen quality specifications for PEM fuel cells, the 2015 target is to ensure no possibility of lubricant contamination of the hydrogen from the compression needed at refueling stations or stationary power sites since this compression is just prior to use on a vehicle or stationary power fuel cell.

[I] The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas hydrogen production case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that two compressors would be needed due to the currently unknown reliability of forecourt compressors, at a total installed capital cost of $600K. The electricity required assumed an isentropic energy efficiency of 70% and an electricity price of $.07/kWhr. The compression operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

[j] For 2003 and 2005, it is assumed that the hydrogen delivery pressure to the vehicle is 5000 psi. For 2010 and 2015, it is assumed that the hydrogen delivery pressure to the vehicle is 1500 psi or less based on the on-board vehicle storage program (Section 3.3) being successful in meeting its targets.

[k] The 2003 cost contribution and electrical energy efficiency was determined using the H2A Delivery Component Model spreadsheet using standard H2A financial input assumptions and the liquefaction spreadsheet tab (www.eere.energy.doe/hydrogenandfuelcells). The H2A spreadsheet information is based on data from other references sited in the H2A Delivery Component Model. References and a plot of liquefier capital cost as a function of capacity and a plot of actual energy used as a function of liquefier capacity are provided in the H2A Delivery Component model.

[l] Electrical energy efficiency is defined as the theoretical energy needed to liquefy the hydrogen divided by the energy actually needed in a hydrogen liquefaction plant. The theoretical energy is that energy needed to cool the gas to the liquefaction temperature and the energy needed for the ortho/para transition. The H2A Delivery Component Model (www.eere.energy.doe/hydrogenandfuelcells) provides the references and a plot of actual energy needed for current hydrogen liquefiers as a function of capacity.

[m] The 2010 hydrogen content targets are based on transporting 1500 kg of hydrogen in a truck. Although regulations vary to some degree by state, a typical truck is limited to carrying 25,000 kg of load and/or 113,000 liters of volume. The minimum hydrogen content (% by weight and kg H2/liter) to achieve 1500 kg of hydrogen on the truck is determined by the maximum loads allowable. Trucking costs with this hydrogen payload are such that this transport option would seem attractive relative to the delivery cost objectives. A typical refueling station of 1500 kg/day of hydrogen servicing hydrogen fuel cell vehicles would service the same number of vehicles as typical gasoline stations serve today. This delivery option would require one

truck delivery per day which is also typical of today's gasoline stations. The 2015 targets are calculated in the same way but assuming 3000 kg per truck load so that the one truck could service two refueling stations. The total cost and attractiveness of this delivery option would depend on the cost of the total carrier delivery system including the cost of discharging the hydrogen at the refueling station and any carrier regeneration costs.

[n] The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that the hydrogen storage installed capital cost is $1.1M based on current technology and 1,100 kg of hydrogen storage. The storage operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

o Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787. Future information on contaminant limits for on-board storage may add additional constraints.

3.2.4.2 Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis. Options and trade-offs for hydrogen/carrier delivery from central and semi-central production to the point of use are not well understood. Distributed production is another option. Analysis is needed to understand the advantages and disadvantages of these various approaches. Many site-specific and regional issues are associated with integrating production and use of hydrogen. Production and delivery systems need to be integrated to minimize cost and take full advantage of local resources and situations.

B. Reliability and Costs of Hydrogen Compression. Compression of natural gas is a well-developed technology. The hydrogen molecule is much smaller than methane, which creates significant challenges for compression. Current compression technology used for hydrogen is unreliable, resulting in the need for redundant compressors and thus higher cost. Centrifugal compression is the lowest cost approach for pipeline compression needs but the current technology does not work with hydrogen. Lubricants used in normal compression applications result in unacceptable contamination of hydrogen for PEM fuel cell use. If high-pressure (5,000 -10,000 psi) on-board hydrogen storage is used for vehicles, this also adds to the compression technology needs for hydrogen. Reliable, lower-cost, more efficient compression technologies are needed.

C. High Cost and Low Energy Efficiency of Hydrogen Liquefaction. Cryogenic liquid hydrogen has a much higher volumetric energy density than gaseous hydrogen. As a result, in the absence of a hydrogen pipeline infrastructure, transporting liquid hydrogen by cryogenic truck is significantly less costly than transporting compressed hydrogen by gaseous tube trailer. However, the cost of the liquefaction step adds very significantly to the cost of delivered hydrogen. In addition, this process is very energy intensive and inefficient (see Table 3.2.2). Improved liquefaction technology is needed. Possibilities include increasing the scale of these operations and improving heat integration, integrating these operations with hydrogen production or power production for improved heat integration and energy efficiency, and completely new liquefaction technologies such as magnetic or acoustic liquefaction or other approaches. In addition, hydrogen boil-off from cryogenic liquid storage tanks and tank trucks needs to be addressed and minimized or eliminated for improved cost and energy efficiency.

D. High Capital Cost and Hydrogen Embrittlement of Pipelines. Existing hydrogen pipelines are very limited and not adequate to broadly distribute hydrogen. Materials, labor and other associated costs result in a large capital investment for new pipelines. Land acquisition or right of way can also be very costly. Hydrogen embrittlement of steel is not completely understood. Current joining technology for steel pipes is a major part of the labor costs and impacts the steel microstructure in a manner that can exascerbate hydrogen embrittlement issues. Hydrogen leakage through the pipe itself, as well as through valves, fittings and seals is much more problematic than for natural gas due to the very small size of hydrogen molecules. Research is needed to determine suitable steels, and/or coatings, or other materials of construction to provide safe and reliable transport of hydrogen in pipelines while reducing the capital costs for materials and labor. Development of innovative materials and technologies (seals, components, sensors, and safety and control systems) is needed. Approaches for using existing natural gas pipelines to transport mixtures of natural gas and hydrogen without hydrogen embrittlement and leakage will be explored. Technologies for low cost separation and purification of hydrogen from natural gas would need to be developed for this approach to hydrogen delivery. The possibility of utilizing or upgrading natural gas or petroleum pipelines for pure hydrogen use also needs to be examined.

E. Solid and Liquid Hydrogen Carrier Transport. Novel solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport and off-board storage. Current solid and liquid hydrogen carrier technologies have high costs, insufficient energy density and/or poor hydrogen release and regeneration characteristics. Substantial improvements in current technologies or new technologies are needed.

F. Hydrogen Delivery Infrastructure Storage Costs. Hydrogen storage at production facilities, refueling stations, and other points of end use, and for system surge capacity for pipelines, trucks and rail at terminals, adds cost to the delivery infrastructure. Understanding and minimizing the need for this storage, while not adversely impacting the market daily and seasonal hydrogen demand cycles, will be important to minimizing these costs. Lower cost technologies to satisfy these storage requirements will also reduce overall delivery costs.

G. Geologic Storage. The feasibility of geologic hydrogen storage needs to be addressed. Geologic storage is routinely used to provide seasonal surge capacity for natural gas and could be equally important for a hydrogen delivery infrastructure. Novel approaches may be needed to deal with the higher diffusivity and potentially higher reactivity of hydrogen as compared to natural gas. Options such as alternative cushion gases coupled with membrane-separation of recovered hydrogen and identification of geologic structures with particularly promising permeability characteristics may need to be examined. Potential environmental impacts need to be investigated.

H. Storage Tank Materials and Costs. Off-board storage tanks required at refueling stations and at other points in the delivery infrastructure add costs to the delivery system not only for the cost of the tanks themselves but also for the cost of the valuable real estate space they consume. They can be impacted by hydrogen embrittlement, as discussed in Barrier D. This can be exacerbated by pressure cycling. Materials research is needed to help resolve hydrogen embrittlement issues. Higher pressures could reduce storage footprint requirements. Research into new materials such as metal ceramic composites, improved resins, and engineered fiber composites is needed. Costs might also be reduced through the use of Design for Manufacture Analysis (DFMA) and mass production of many identical storage units.

I. Hydrogen Leakage. The hydrogen molecule is very small and diffuses more rapidly compared with other gases such as natural gas. This makes it more challenging to design equipment, materials, seals, valves and fittings to avoid hydrogen leakage. Current industrial hydrogen operations are monitored and maintained by skilled people. The delivery infrastructure for hydrogen use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering.

J. Safety, Codes and Standards, Permitting and Sensors. Appropriate codes and standards are needed to ensure a reliable and safe hydrogen delivery infrastructure. Some of the hydrogen delivery elements such as tube trailers and cryogenic liquid hydrogen trucks are in commerce today. Others are not, such as an extensive pipeline infrastructure for transmission and distribution and terminal operations. Applicable codes and standards are needed to facilitate provision for off-board storage at refueling stations and upstream in the hydrogen supply chain. More cost-effective sensors for leak detection and other purposes need to be developed. Sighting and permitting hurdles need to be overcome. The plan to address these issues is in the Codes and Standards section (Section 3.6).

3.2.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.2.3. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate Program element.

Table 3.2.3. Technical Task Descriptions

Task	Description	Barriers
1	**Delivery Infrastructure Analysis** • Characterize the current cost and energy efficiency of the components and complete pathways for gaseous and liquid hydrogen and identify the key cost reductions and energy efficiency improvements needed. • Characterize the cost boundaries of novel solid and liquid hydrogen carrier systems for delivery. • Perform analysis to examine the options and trade-offs of hydrogen/carrier delivery infrastructures and identify cost-effective, energy-efficient and safe hydrogen delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power. • Analyze and optimize the trade-offs and costs at refueling stations relative to the amount and pressure of hydrogen storage, compression needs, and the utilization factor for distributed hydrogen production.	A, B, C, D, E, F, G, H, I, J

2	**Reliable, Energy-Efficient, and Lower Cost Hydrogen Compression Technology** • Research existing and novel hydrogen compression technologies that can improve reliability, eliminate contamination, and reduce cost. • Develop reliable, low cost, energy efficient compression technology for hydrogen pipeline transmission service. • Develop reliable, low cost, energy efficient compression technology for hydrogen refueling station needs.	B, I
3	**Lower Cost and Energy-Efficient Hydrogen Liquefaction Technology** • Investigate cost and energy efficiency gains for larger scale operations, achieving additional energy integration, and improving refrigeration schemes. • Explore new and novel breakthrough technologies such as magnetic-caloric liquefaction.	C
4	**Hydrogen Gas Pipeline Technologies** • Research and identify preventative measures for hydrogen embrittlement and permeability in steel pipelines, including in the delivery of mixtures of hydrogen and natural gas. • Research improved steel pipe joining methods and other approaches to reduce capital cost and hydrogen embrittlement concerns. • Research and develop coating technology for steel or other possible pipeline materials to resolve hydrogen embrittlement and permeation issues. • Research and develop alternative materials to steel for hydrogen pipelines that could reduce capital cost while providing safe and reliable operations. • Develop improved and lower cost valves, fittings and seals to reduce hydrogen leakage. • Define available right of way and probable right of way costs for a complete hydrogen pipeline infrastructure. • Analyze, investigate, and develop technologies for existing natural gas pipelines for transporting hydrogen and natural gas mixtures (including technology to cost-effectively separate and purify the hydrogen) and for upgrading natural gas pipelines for pure hydrogen.	D, I
5	**Hydrogen Carrier Technologies** • Develop novel solid or liquid hydrogen carrier technologies for high volumetric energy density, low-cost transport and/or storage of hydrogen.	B, C, D, E, F, G, H. I, J

6	**Off-Board Hydrogen Storage** • From the outputs of Task 1, characterize the R&D requirements for off-board storage including storage options at refueling stations and throughout the delivery infrastructure. • Research the feasibility of geologic storage as a low cost storage option. • Develop more cost effective hydrogen storage technology by researching areas including: tank materials, novel carriers, and the use of DFMA and high throughput production methods. • Identify the needs and initiate any appropriate research for the interface requirements, including thermal management, between the refueling station compression, storage and dispensing and the on-board vehicle storage system, during refueling.	B, E, F, G, H, I, J

3.2.6 Milestones

Figure 3.2.4 shows the interrelationship of milestones, tasks, supporting inputs from other program elements, and technology program outputs for the Hydrogen Delivery program element from FY 2004 through FY 2010. This information is also summarized in Table B.2 in Appendix B.

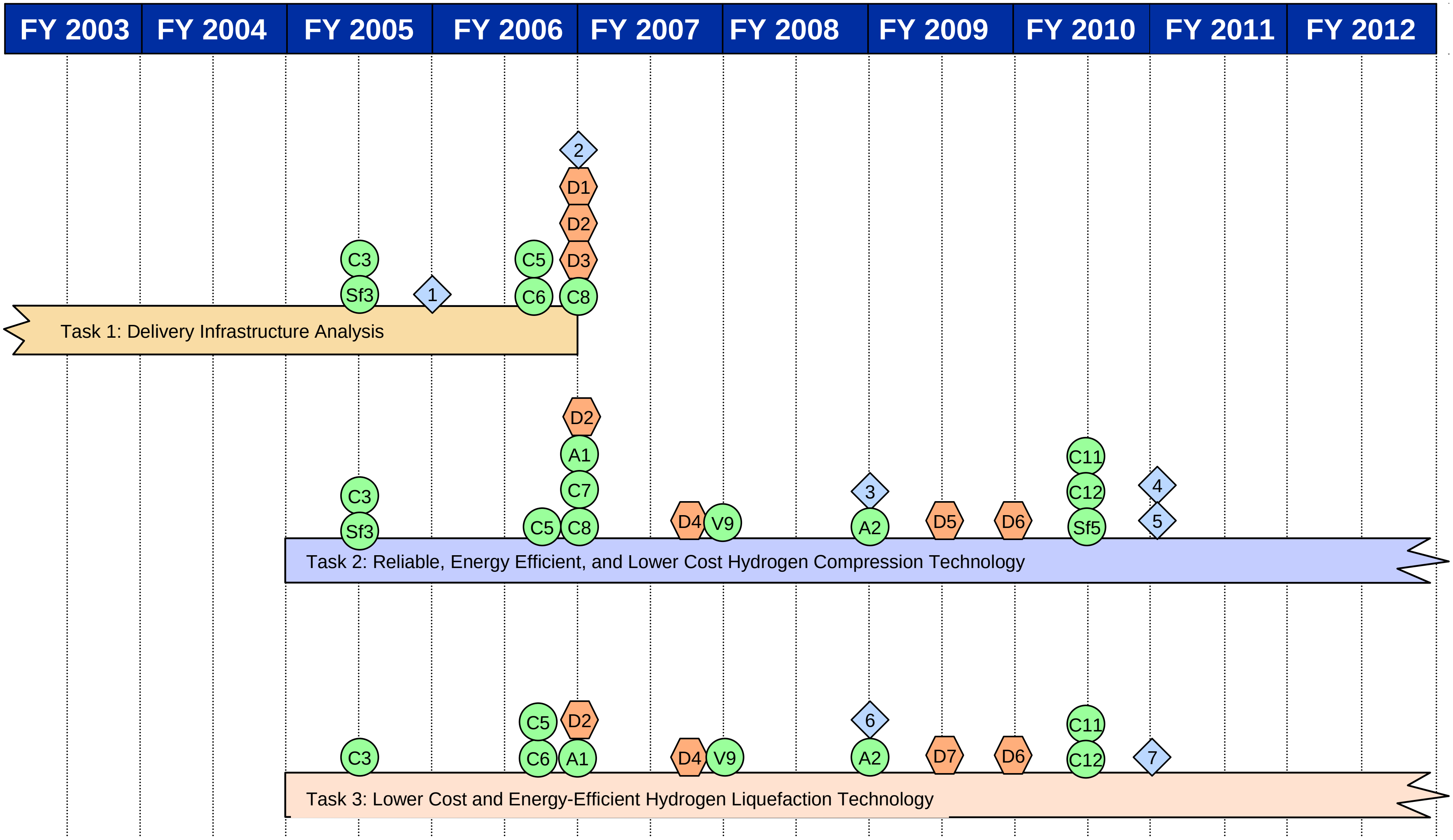
Footnotes:

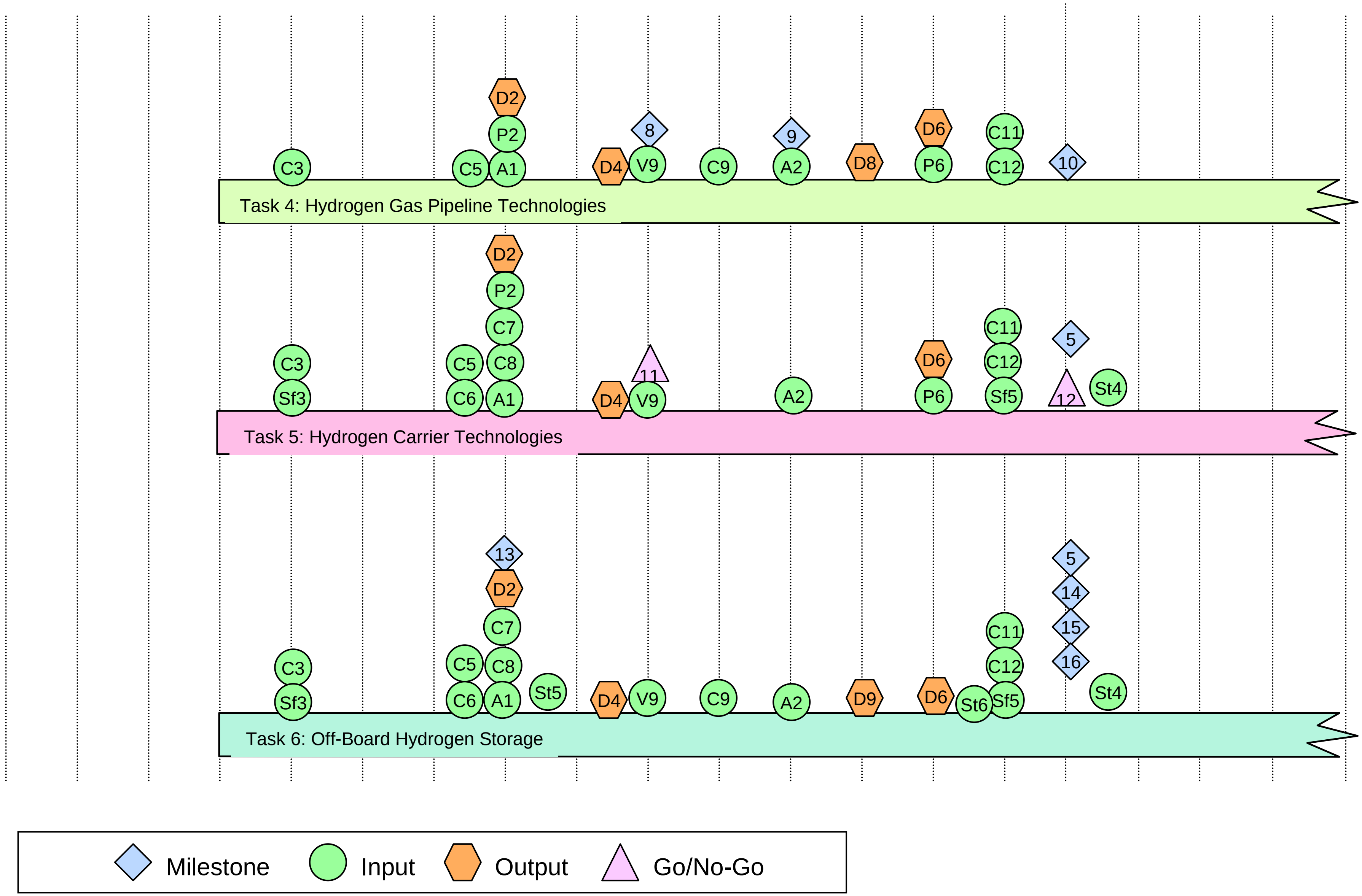
[1] These targets are based on a well-established hydrogen market demand for transportation. The specific scenario examined assumed central and semi-central production of hydrogen servicing small (~100,000 people) and large (~1,000,000 people) cities.

[2] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. National Research Council and National Academy of Engineering of the National Academies. National Academies Press, Washington, c2004.

[3] Chemical and Market Reporter, February 24, 2003, p. 43.

Hydrogen Delivery R&D Milestone Chart





D2
P2
C3
C5
A1
8
D4
V9
C9
9
A2
D8
D6
P6
C11
C12
10
Task 4: Hydrogen Gas Pipeline Technologies
D2
P2
C7
C3
Sf3
C5
C8
C6
A1
11
D4
V9
A2
D6
P6
C11
C12
Sf5
5
12
St4
Task 5: Hydrogen Carrier Technologies
13
D2
C7
C3
Sf3
C5
C8
C6
A1
St5
D4
V9
C9
A2
D9
D6
St6
Sf5
C11
C12
5
14
15
16
St4
Task 6: Off-Board Hydrogen Storage
Milestone
Input
Output
Go/No-Go

Milestones

1 Characterize the current cost and energy efficiency of the components and complete pathways for gaseous and liquid hydrogen delivery and the cost boundaries of potential novel solid and liquid carrier systems.
2 Identify cost-effective options for hydrogen delivery infrastructure to support the introduction and long-term use of hydrogen for transportation and stationary power.
3 Down select to 2-3 most promising compression technologies for hydrogen transmission, refueling, and other needs in delivery.
4 Verify 2010 targeted costs and performance for hydrogen compression (transmission and forecourt).
5 Verify achieving a refueling station cost contribution for compression, storage and dispensing of $0.80/gge of hydrogen
6 Down-select to most promising 1-2 liquefaction technologies.
7 Verify 2010 targeted cost and performance for hydrogen liquefaction.
8 Research identifies fundamental mechanism of hydrogen embrittlement and permeation in steel pipelines and identifies promising cost effective measures to mitigate these issues. (4Q 2007)
9 Down-select on materials and/or coatings for pipelines including the potential use of natural gas pipelines for mixtures of natural gas and hydrogen, or hydrogen alone.
10 Verify 2010 targeted cost and performance for hydrogen pipelines. (4Q 2010)
11 Go/No-Go: Initial down-select for potential solid or liquid carrier systems for hydrogen delivery based on cost boundary analysis and initial research efforts.
12 Go/No-Go: Verify the feasibility of a hydrogen carrier system to meet the 2010 carrier targets. (4Q 2010)
13 Complete baseline analyses of off-board storage options at refueling stations and throughout the delivery infrastructure. (4Q 2006)
14 Complete the research to establish the feasibility and define the cost for geologic hydrogen storage.
15 Down-select to the most promising 1-2 technologies for off-board storage.
16 Verify the feasibility of achieving the 2010 refueling station storage cost targets. (4Q 2010)

Outputs

D1 Output to Storage, Systems Analysis and Systems Integration: Assessment of cost and performance requirements for off-board storage systems.
D2 Output to Storage and Fuel Cells: Hydrogen contaminant composition and issues.
D3 Output to Technology Validation, Systems Analysis and Systems Integration: Hydrogen delivery infrastructure analysis results.
D4 Output to Systems Analysis and Systems Integration: Assessment of impact of hydrogen quality requirements on cost and performance of hydrogen delivery.
D5 Output to Technology Validation: Compression technology recommended for validation.
D6 Output to Systems Analysis and Systems Integration: Update of hydrogen quality requirements.
D7 Output to Technology Validation: Recommended liquefaction technology for potential validation.
D8 Output to Technology Validation: Recommended pipeline technology for validation.
D9 Output to Storage and Technology Validation: Recommended off-board storage technology for validation.

Inputs

C3 Input from Codes and Standards: Preliminary assessment of Safety, Codes and Standards for the hydrogen delivery infrastructure.
Sf3 Input from Safety: Safety requirements and protocols for refueling.
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
C6 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.
C8 Input from Codes and Standards: Draft standards (balloting) for refueling stations (NFPA).
A1 Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.
C7 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system
C11 Input from Codes and Standards: Codes and Standards for the delivery infrastructure complete.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.
P2 Input from Production: Assessment of fuel contaminant composition.
C9 Input from Codes and Standards: Materials compatibility technical reference.
P6 Input from Production: Assessment of fuel contaminant composition.
St4 Input from Storage: Report on full-cycle chemical hydrogen system and evaluation against 2010 targets (1Q 2011)
St5 Input from Storage: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.
St6 Input from Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc.) and down-select to a primary on-board storage system candidate.